Modal MAC Launch Loads for SMAP Structural Design

Walter S. Tsuha
Chia-Yen P. Peng
Jet Propulsion Laboratory
California Institute of Technology

Mechanical Systems Engineering
Spacecraft Structures and Dynamics
19–21 June 2012

Overview

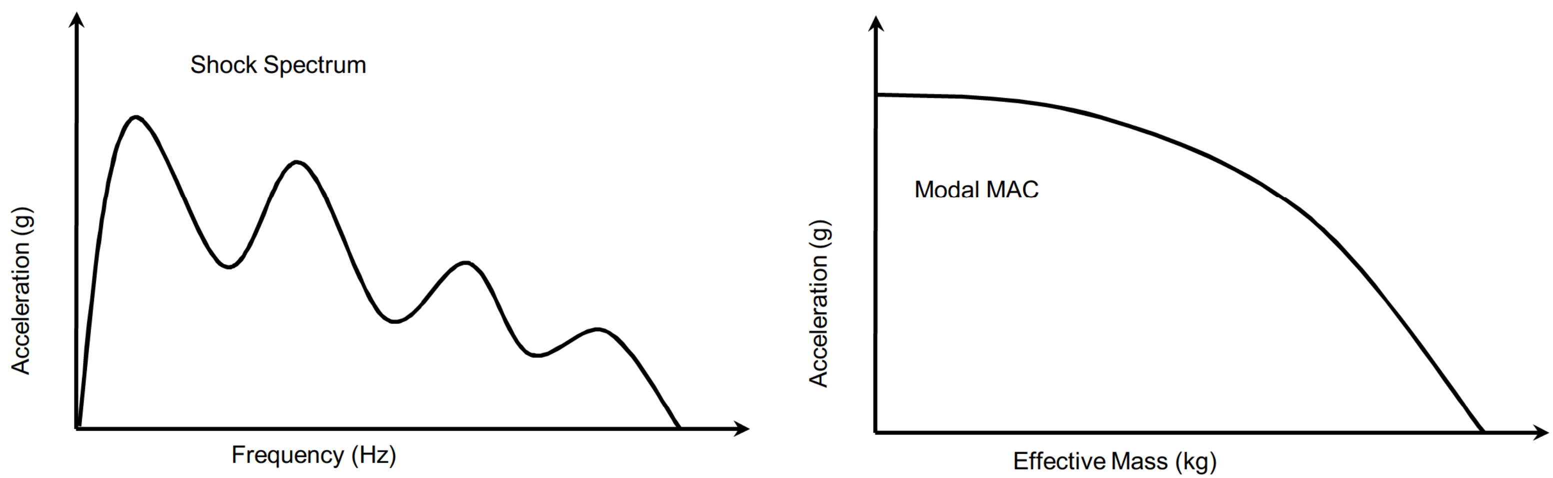
- Overview
  - *Describe an effective methodology for generating limit loads for payload structural design that bound results from a Coupled Loads Analysis (CLA)*
  - *Effectiveness of the methodology is demonstrated for a current program at JPL*
- Modal Mass Acceleration Curve (MAC) Loads Analysis
  - *Background*
  - *Modal MAC Bound*
  - *SMAP Results*

Modal MAC Loads Analysis - Background (1/3)

- **Bounding Loads** – Methodology generates bounding loads for the low frequency launch dynamic environments (< 100 Hz) for structural design
  - *Not a simulation, but bound loads from a CLA*
- **Quick Turnaround** – Loads analysis for a payload (e.g., spacecraft) accomplished in 1 – 2 weeks, as opposed to the typical 2 - 3 month turnaround time for a coupled loads cycle
  - *Modal MAC Analysis*   *1 – 2 Weeks*
  - *Coupled Loads Analysis*   *2 – 3 Months*
- **Accommodates Large Output Requests** – Possible to output loads for an entire payload model
  - *Modal MAC Analysis*   *> 500,000 Output Items*
  - *Coupled Loads Analysis*   *< 10,000 Output Items*

Modal MAC Loads Analysis - Background (1/3)

- **Modal MAC analysis is essentially a response spectrum analysis** in which the maximum SDOF response is given by the modal MAC, instead of the traditional shock spectrum

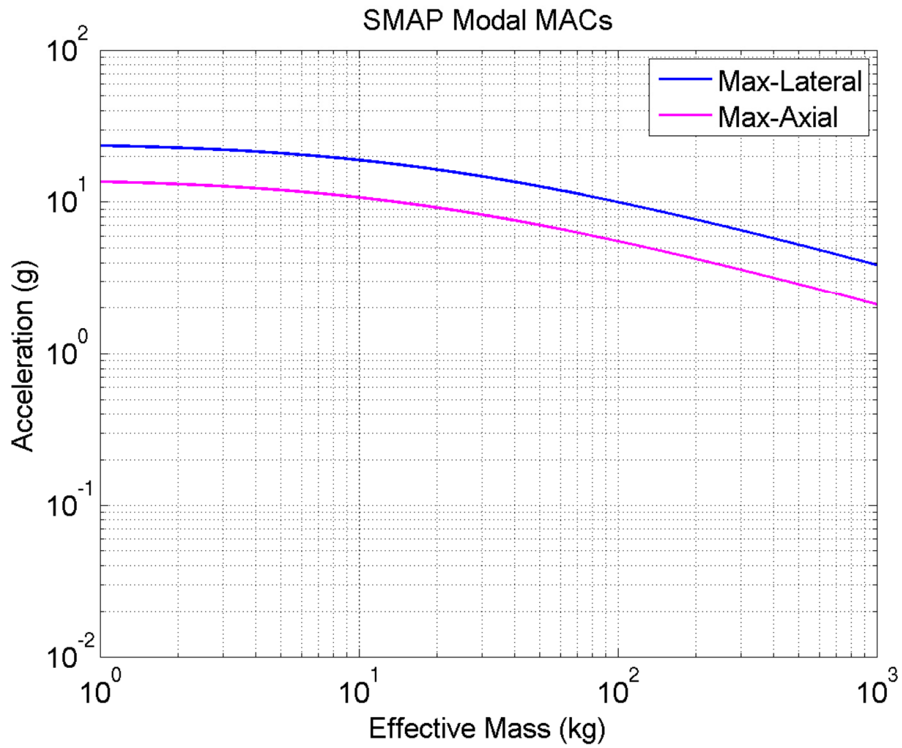


- Each mode represents a spring-mass system cantilevered from the payload to launch vehicle interface with some “effective mass”
- Physical loads are obtained by RSSing the modal bounds, as in a response spectrum analysis
- Modal MAC is based on the observation that the acceleration of a mass is inversely proportional to the square-root of its mass

AEROSPACE

Modal MAC Loads Analysis - Background (3/3)

- **Inputs**
  - *FEM of Payload*
    - Compute modes, frequencies, effective masses, etc.
  - *Modal Mass Acceleration Curve*
  - *Payload to Launch Vehicle Interface Accelerations*
- **Typical Load Cases**
  - *Max-Lateral*
    - 2 – 3 g Lateral
    - 3 – 4 g Axial
  - *Max-Axial*
    - 0.5 – 0.8 g Lateral
    - 6 – 9 g Axial



Modal MAC Bound (1/3)

- **Payload Dynamic Equations**

$$M\ddot{x}(t)+Kx(t)=f(t), \qquad M \ \& \ K: \text{ Payload Mass and Stiffness Matrices}$$

- **Craig-Bampton Coordinate Transformation**

$$x(t)\cong Tq(t)=\begin{bmatrix}\Phi^{cm} & \Phi^{nm}\end{bmatrix}\begin{Bmatrix}x_r(t)\\ q_k(t)\end{Bmatrix} \qquad \begin{matrix}\Phi^{cm} & \text{Rigid-body Modes}\\ \Phi^{nm} & \text{Fixed-Interface Modes}\end{matrix}$$

- **Craig-Bampton Model (Determinate Interface)**

$$\begin{bmatrix}M_{rr} & M_{er}^T\\ M_{er} & I_{kk}\end{bmatrix}\begin{Bmatrix}\ddot{x}_r(t)\\ \ddot{q}_k(t)\end{Bmatrix}+\begin{bmatrix}0 & 0\\ 0 & 2\Xi_{kk}\Omega_{kk}\end{bmatrix}\begin{Bmatrix}\dot{x}_r(t)\\ \dot{q}_k(t)\end{Bmatrix}+\begin{bmatrix}0 & 0\\ 0 & \Omega_{kk}^2\end{bmatrix}\begin{Bmatrix}x_r(t)\\ q_k(t)\end{Bmatrix}=\begin{bmatrix}f_r(t)\\ 0\end{bmatrix}$$

$$M_{rr}=(\Phi^{cm})^T M\Phi^{cm} \qquad \text{Rigid-Body Mass Matrix}$$

$$M_{er}=(\Phi^{nm})^T M\Phi^{cm} \qquad \text{Elastic-Rigid Mass Coupling Matrix}$$

$$\Xi_{kk}=diag\begin{Bmatrix}\xi_1 & \cdots & \xi_k\end{Bmatrix} \qquad \text{Diagonal Modal Mamping Matrix}$$

$$\Omega_{kk}=diag\begin{Bmatrix}\omega_1 & \cdots & \omega_k\end{Bmatrix} \qquad \text{Diagonal Modal Freuqency Matrix}$$

AEROSPACE

Modal MAC Bound (2/3)

- **Acceleration (Exact Time Consistent Solution)**

$$\ddot{x}(t) = \begin{bmatrix} \Phi^{cm} & \Phi^{nm} \end{bmatrix} \begin{Bmatrix} \ddot{x}_i(t) \\ \ddot{q}_k(t) \end{Bmatrix} = \sum_{i=1}^{r} \phi_i^{cm} \ddot{x}_i(t) + \sum_{s=1}^{k} \phi_s^{nm} \ddot{q}_s(t)$$

- **Conservative Bound**

$$\ddot{x}(t) \leq \sum_{i=1}^{r} \left| \phi_i^{cm} \ddot{x}_i^{\max} \right| + \sum_{s=1}^{k} \left| \phi_s^{nm} \ddot{q}_s^{\max} \right|$$

$$\ddot{x}_i^{\max} = \max_{0 \leq t \leq T} (\ddot{x}_i(t)), \quad \ddot{q}_s^{\max} = \max_{0 \leq t \leq T} (\ddot{q}_s(t)), \quad i = 1:r, \quad s = 1:k$$

- **Modal MAC Bound** (Simplified Version for Clarity)

$$\ddot{x}(t) \leq \sum_{i=1}^{r} \left| \phi_i^{cm} \ddot{x}_i^{mmac} \right| + \sqrt{\sum_{s=1}^{k} \left(\phi_s^{nm} \sqrt{m_s^{eff}} \, \ddot{q}_s^{mmac} \right)^2}$$

$\ddot{x}_i^{mmac}$ = Bound of Payload to LV Interface Acceleration

$\sqrt{m_s^{eff}}$ = Square-Root of Effective Mass

$\ddot{q}_s^{mmac}$ = Modal MAC Acceleration $\geq \dfrac{\ddot{q}_s^{\max}}{\sqrt{m_s^{eff}}}$

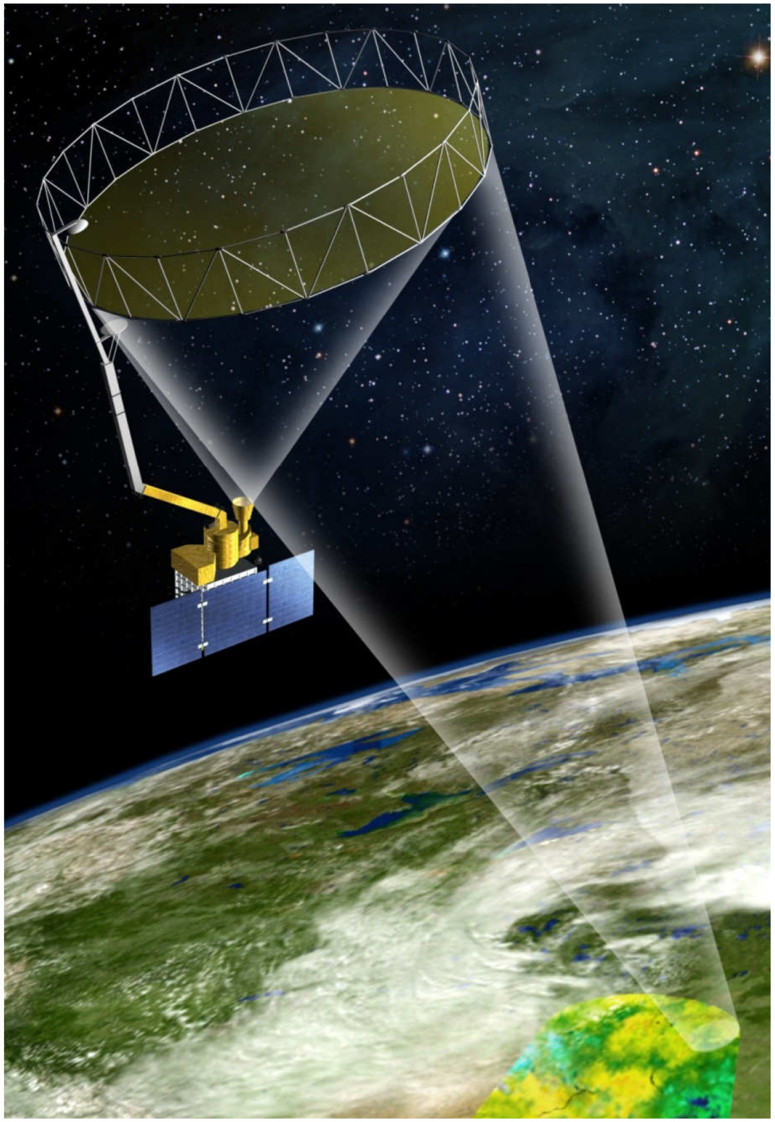
AEROSPACE

Modal MAC Bound (3/3)

- Bounding loads are generated if the following conditions are satisfied
  1. ***Condition 1:*** *Modal MAC bounds all payload generalized coordinate accelerations from the CLA.*
  2. ***Condition 2:*** *Modal MAC interface accelerations bound all payload to launch vehicle interface accelerations from the CLA.*

- In practice, however, the above conditions are conservative, and the following is done instead
  1. ***Condition 1 is enforced.*** *Modal MAC is set to bound all payload generalized coordinate accelerations from the CLA.*
  2. ***Condition 2 is not strictly enforce.*** *Modal MAC interface accelerations are adjusted so that the overall c.g. load factors from the modal MAC analysis bound the load factors given in the Payload Planner's Guide and CLA.*

Soil Moisture Active Passive (SMAP) Mission

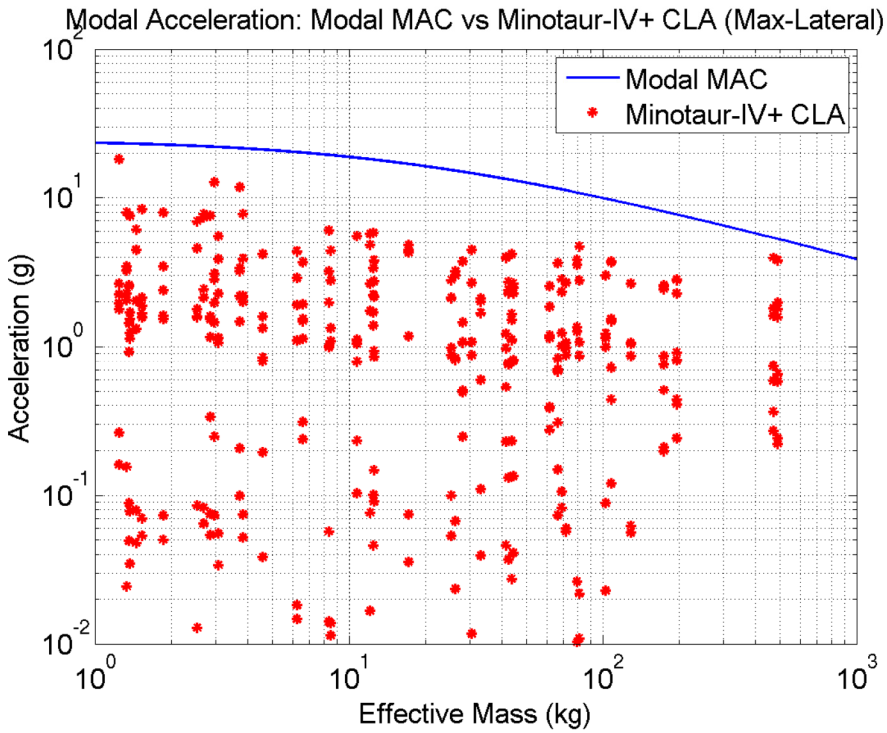


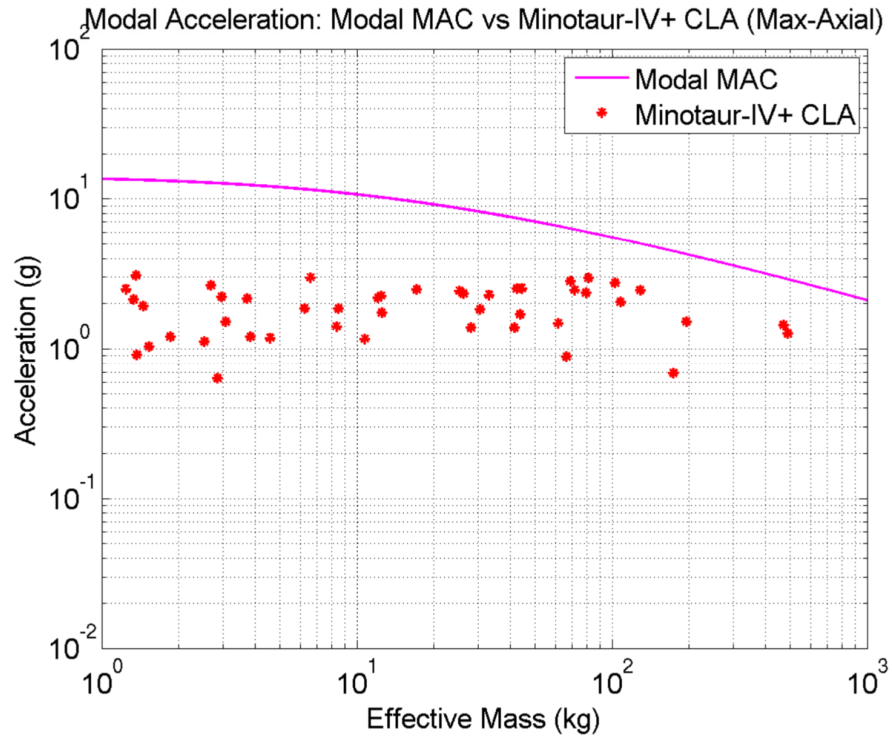
- **Mission Objective:** Provide global measurements of soil moisture and its freeze/thaw state
  - *Measurements will be used to*
    - enhance our understanding of processes that link the water, energy and carbon cycles
    - extend the capabilities of weather and climate prediction models
- **Candidate Launch Vehicles**
  - *Minotaur-IV$^+$*
  - *Delta-II 7320*
  - *Falcon-9*
  - *SMAP must be designed to survive launch on any one of these launch vehicles*

AEROSPACE

SMAP Modal MAC Analysis Results (1/3)

Modal MAC vs. CLA Generalized Coordinate Accelerations





- Modal MAC bounds generalized coordinate accelerations from SMAP/Minotaur-IV$^+$ CLA
- Similar comparisons were obtained for the SMAP/Delta-II 7320 CLA
- Therefore, modal MAC loads should bound loads from these CLAs

SMAP Modal MAC Analysis Results (2/3)

C.G. Load Factors – Modal MAC vs. CLA

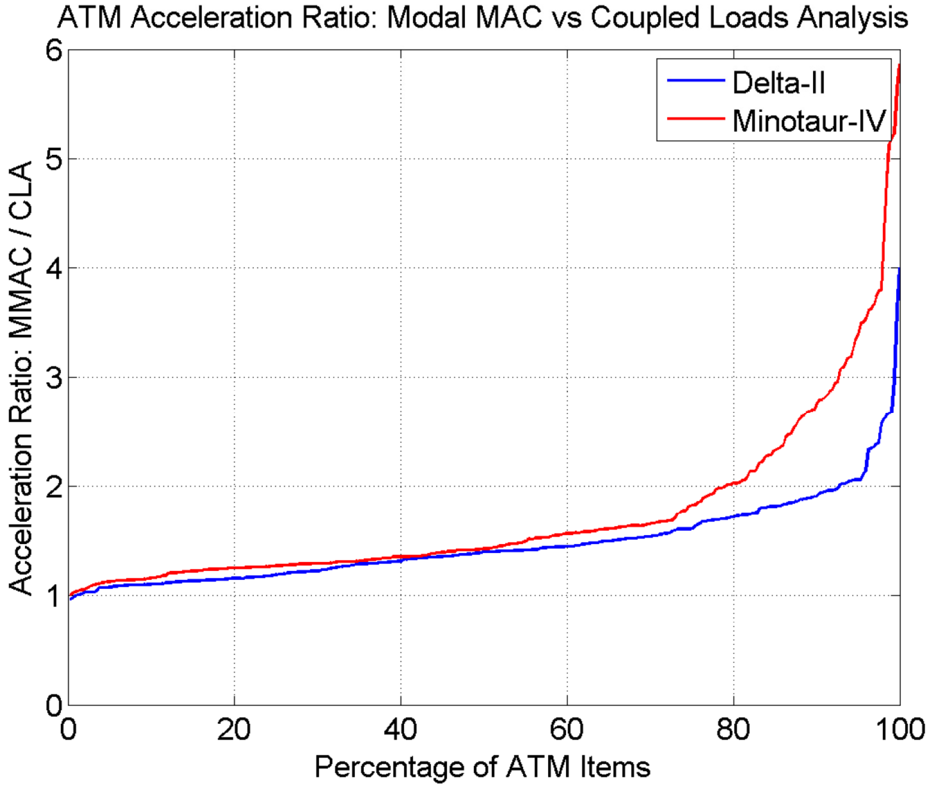
SMAP C.G. Load Factors

Load Description	Acceleration (g)					
	Payload Planner's Guide			Coupled Loads		Modal MAC
	Falcon-9	Minotaur-IV	Delta-II	Minotaur-IV+	Delta-II 7320	
Max-Lateral						
Lateral	2.0	2.9		3.0	2.7	3.0
Axial	3.5	4.0	2.8	4.9	2.8	5.1
Lateral (Moment-Based)			3.5	3.9	3.8	4.3
Max-Axial						
Lateral	0.5	---	0.2	0.7	N / A	1.4
Axial	6.0	9.7	8.0	7.6		9.6

- Modal MAC C.G. load factors bound values from the Minotaur-IV$^+$ and Delta-II 7320 CLAs and Payload Planner's Guide
- Some C.G. load factors from CLA exceeded values specified in the Payload Planner's Guide

SMAP Modal MAC Analysis Results (3/3)

ATM Acceleration Ratios – Modal MAC / CLA



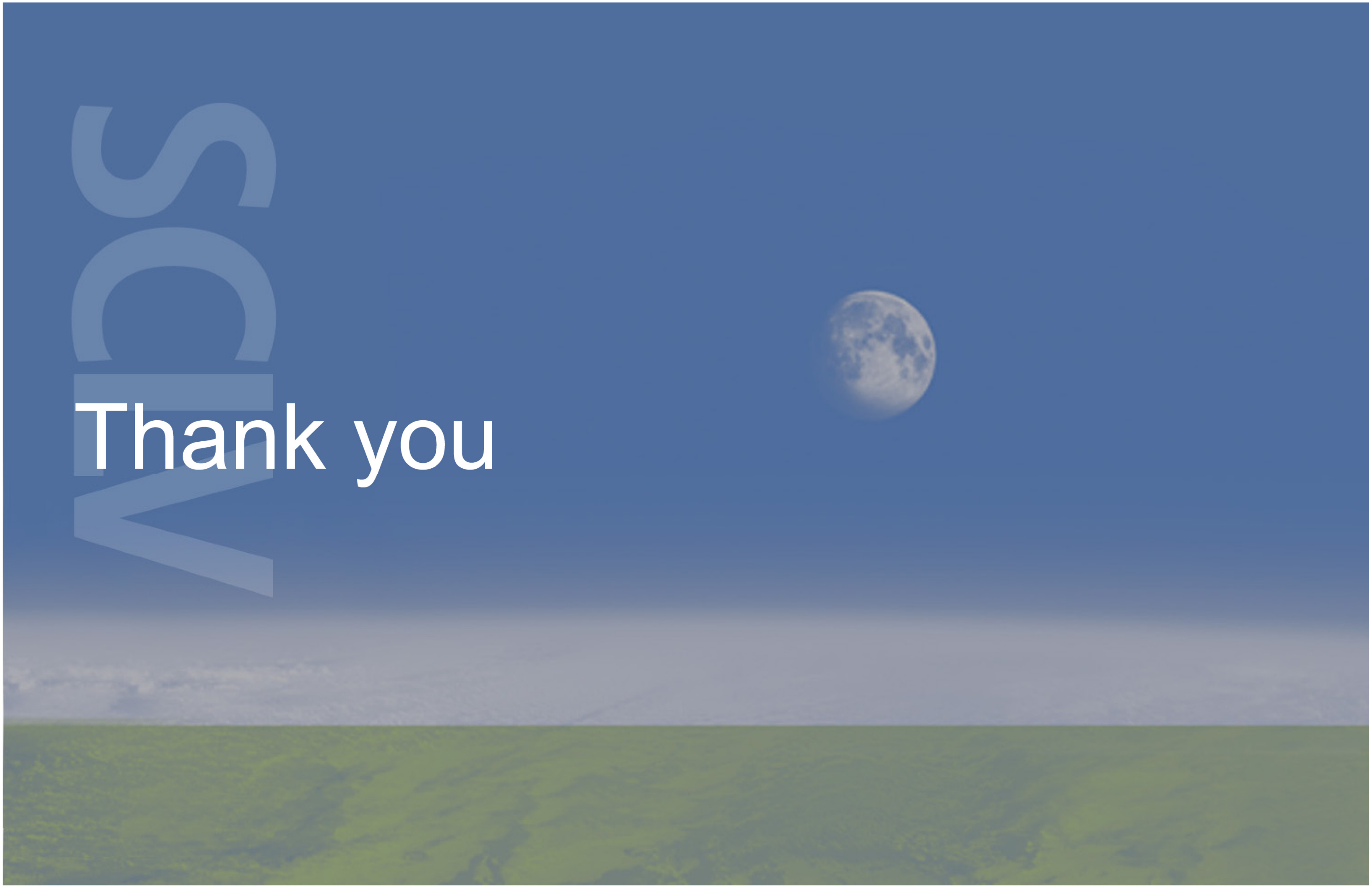
- ATM accelerations from modal MAC analysis bound those from the CLA
- Similar comparisons were obtained for the DTM and LTM
- Therefore, modal MAC loads bound those from the Minotaur-IV^{+} and Delta-II 7320 CLAs

AEROSPACE

Summary and Conclusions

- Modal MAC Analysis
  – ***Bounding Loads**: Generates launch loads that bound loads from a CLA*
  – ***Quick Turnaround**: 1 – 2 weeks vs. 2 – 3 months for a CLA*
  – ***Large Output Requests**: Able to generate loads for an entire payload (>500,000 outputs)*
  – *Efficient and inexpensive method for generating bounding loads for design iterations of an entire payload*
- SMAP Example: Demonstrated that modal MAC analysis results bound those from the Minotaur-IV^{+} and Delta-II 7320 CLAs

AEROSPACE


Thank you